APPENDIX B: HAZARDOUS WASTE LANDFILL COVER DESIGN CONSIDERATIONS

B-1. General

a. *Intended use of document*. This document for landfill cover design was developed to aid in project planning, scheduling, and budgeting; scoping predesign investigations and A/E services; as a guidance document for conducting landfill cover designs; for use in reviewing A/E products; and as a source for technical references. The document is divided into three appendices: Appendix A, References; Appendix B, Hazardous Waste Landfill Cover Design Considerations; and Appendix C, Landfill Cover Design Checklist. Appendix B briefly discusses design aspects for the cover components. Appendix C contains a list of questions covering pertinent aspects of design that were discussed in Appendix B.

b. *Purpose and function of cover system*. Various types of landfill covers are used to close municipal solid waste landfills, hazardous waste landfills, and other types of hazardous waste sites. The primary purpose of a landfill cover is to isolate waste materials from the environment by minimizing the infiltration of surface water, collecting leachate escaping from the side slopes of the waste materials, preventing human and animal contact with the waste materials, and controlling landfill gases. A landfill cover also provides for the controlled release of surface runoff to prevent excessive erosion of the cover system or adverse impacts on adjacent waterways and properties.

c. *Alternative cover types*. The components of a cover system are dependent on functional, environmental, regulatory, and site-specific parameters. The Environmental Protection Agency's (EPA) Resource Conservation and Recovery Act (RCRA) provides guidance on landfill cover configurations for both municipal solid waste and hazardous waste landfills. The federal guidelines for closure of municipal solid waste landfills are set forth in 40 CFR Part 258. The federal guidelines for closure of hazardous waste landfills are set forth in 40 CFR Part 264. State and local governmental agencies may have established their own criteria for cover systems that are more stringent than federal guidelines. The most stringent regulations or guidelines usually govern the design.

d. *RCRA hazardous waste landfill covers*. This document will focus on covers for RCRA hazardous waste landfills. In general, the components of a hazardous waste landfill cover consist of a protective cover layer, a drainage layer, a low permeability layer composed of a geomembrane over a low permeability soil component, and random fill overlying the waste. Optional layers include a gas collection system and a biotic barrier. Biotic barriers are placed in the upper portions of a landfill cover to prevent plants and animals from damaging the cover. However, they are rarely used and will not be discussed in this document. Site-specific physical conditions such as topography, material availability, and cover stability impact the design and material selection of the cover components. A typical RCRA hazardous waste landfill cover design incorporating all the optional layers is presented in Figure B-1.

e. *Project team*. Provided below is a list of members for an idealized design/review team for a landfill cover project. For most projects, the design or review team will not include individuals from each of the noted disciplines. Consequently, it is important that all aspects of design are assigned to a member of the team. Team members include:

- Customer.
- Project manager.
- Technical manager.
- Project engineer.
- Geotechnical engineer.
- Geologist.
- Mechanical engineer.
- Electrical engineer.
- Hydrologist.
- Hydraulic engineer.

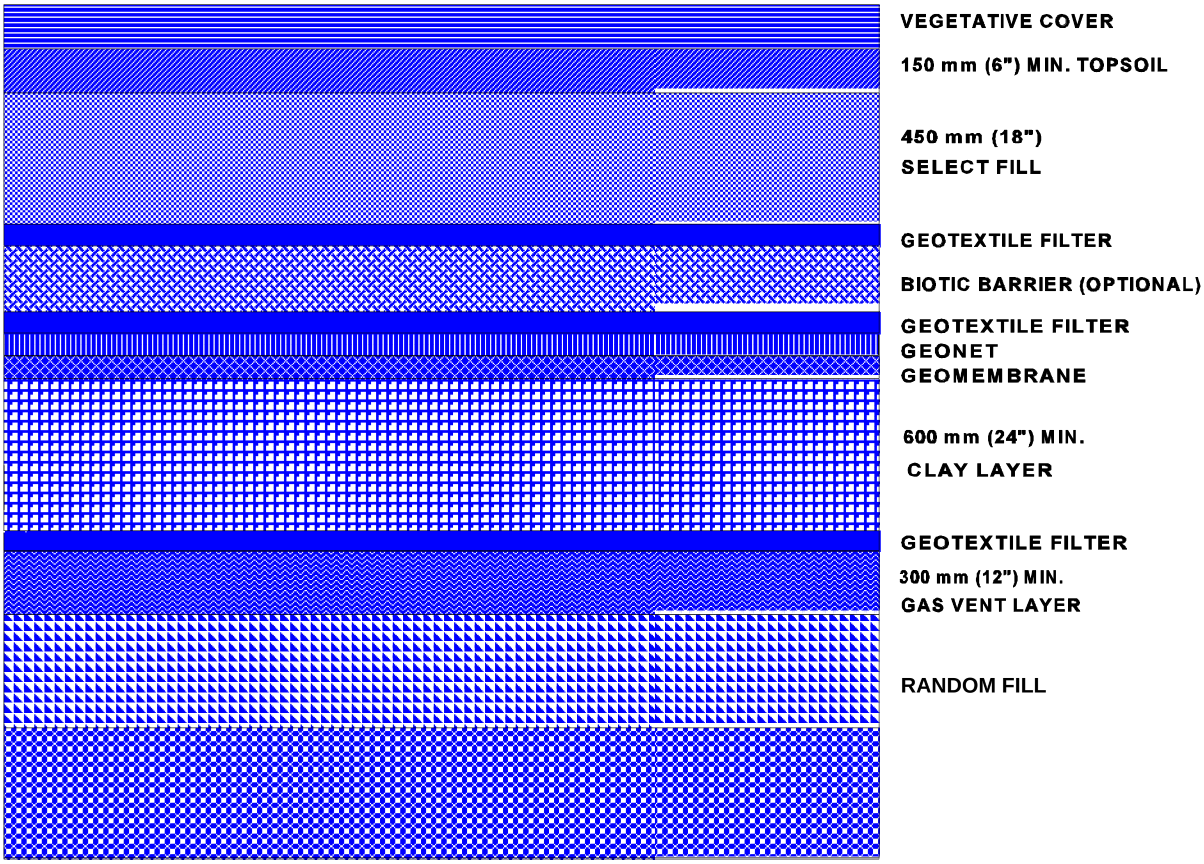

Figure B-1. Typical RCRA hazardous waste landfill cover design with all optional layers

- Civil engineer.
- Environmental engineer.
- Materials engineer.
- Industrial hygienist.
- Chemist.
- Land surveyor.
- Landscape architect.
- Drafter/CADD technician.
- Specifications writer.
- Cost estimator.
- Regulatory specialist.
- Real estate specialist.
- Construction representative.
- Local, state, and federal regulatory staff.

B-2. Predesign Investigations

a. *General*. Prior to preparing a design analysis or plans and specifications for a landfill cover, it is necessary to conduct predesign surveys and investigations to fill data gaps. The existing data base available from the remedial investigation (RI), feasibility study (FS), and any other documents must be reviewed before scoping a predesign effort. The following information is often required in the design of a final cover.

b. Field surveys and record searches.

(1) Aerial photography. Historic aerial photographs can be used to preliminarily define the nature and extent of a landfill. The principal sources of aerial photographs are the U.S. Department of Agriculture (USDA) Agricultural Stabilization and Conservation Service (ASCS) and the U.S. Geological Survey (USGS).

(2) Design and operational data. Design and operational information such as as-built drawings, specifications, and design analyses may help in identifying the nature and extent of a landfill. However, documents such as these are rarely available for existing hazardous waste sites.

(3) Map data base. The USGS, USDA, and other government agencies produce topographic, soils, ground water, and other mapping that may be useful in defining landfill boundaries and cover design.

(4) Topographic surveys. Current topographic surveys of the project site are required. To allow for manipulation of data and to expedite the design process, the topographic survey should be mapped on a computer-aided design and drafting (CADD) system. Ideally, the topographic mapping will have 300-mm (1-ft) contour intervals because of the thin component layers involved with the cover design. However, larger contour intervals may be acceptable depending on site-specific conditions (e.g. time, budget, topography, etc.). The topographic mapping should be referenced to the horizontal and vertical control used to perform the survey and should be accurate to within $\pm$30.0 mm ($\pm$0.1 ft) in the vertical and horizontal directions. Elevations of piezometers, monitoring wells, or other instrumentation should be accurate to $\pm$3.0 mm ($\pm$0.01 ft) to allow for accurate interpretation of data. All surface features such as buildings, utilities, ponds, fences, trees, streams, ditches, and exploratory borings and trenches should be delineated on the mapping.

(5) Horizontal and vertical control. At a minmum, three permanent control monuments need to be established. The monuments should be strategically located so that they are not damaged during construction and will not be affected by settlement of the landfill or other processes. All monuments should be assigned state plane coordinates and/or tie into the horizontal grid used in previous studies. The vertical datum should be mean sea level.

(6) Monitoring baseline data. To monitor design concerns, it is often necessary to collect an initial set of data to establish a baseline for instrumentation such as settlement gauges, monitoring wells, piezometers, and slope movement markers.

(7) Utilities. All onsite above and below ground utilities need to be located. A utility search should consist of an onsite inspection, review of as-built drawings, and contacts with utility companies. The project drawings should show the location of onsite utilities including horizontal alignment, depth or height, type, and size.

(8) Boundary survey and property search. A boundary survey should be performed for all prop erties or parcels within project construction and access limits. The boundary survey should be tied to the site's horizontal control. A property search should also be performed to identify property owners of all affected and adjacent parcels of land. Prior to any investigation or construction activity, it is essential to obtain construction easements and project right-of-way. This may take 12 to 18 months; therefore, coordination with real estate elements should begin as soon as possible.

c. Geological investigations. After the existing data base has been reviewed, geological investigations can then be scoped. The following items need to be investigated in order to design a cover system.

(1) Landfill limits. It is imperative that the limits of the landfill or contaminated area be defined. Depending on the composition of the waste material, the limits of the landfill can be tentatively defined by geophysical methods such as electromagnetic conductivity surveys and soil gas surveys. Surface depressions and stressed vegetation along with historic aerial photographs can also help in delineating approximate landfill boundaries. Intrusive methods such as test pits or borings should be used to verify landfill boundaries. All test pits and borings should be logged by a qualified geologist or geotechnical engineer. Surveys should also be performed to determine the exact location of any geotechnical investigations used to define the landfill boundary,

and this information should be recorded on the project drawings.

(2) Material excavatability. When a project feature such as a leachate collection trench is required, the excavatability of the subject material should be evaluated. Information that may be required is dependent on site-specific conditions but could include material type, water table elevation, leachate level, moisture content, stratigraphy, rock hardness, rippability, etc. See ETL 1110-2-282 for more information on rock excavation.

(3) Landfill gas. Soil gas surveys or soil gas probes installed on the landfill surface can be used to determine if the landfill is emitting methane and other gases. Pump tests can also be used to define landfill gas emission rates. EPA-450/3-90-011a, "Air Emissions from Municipal Solid Waste Landfills," provides information on methods of estimating landfill gas emissions using pump tests.

(4) Landfill composition. If it is necessary to excavate waste material in order to minimize earthwork, to construct leachate collection trenches, or for other reasons, the composition of the waste should be determined.

(5) Leachate. In some situations leachate may migrate laterally and exit at the surface of the existing landfill. The surface of the landfill should be inspected and leachate seepage exit areas surveyed and mapped. Drainage layers to collect this seepage may need to be a component of the landfill cover. The leachate should be characterized since its composition will affect the selection of drainage layer materials and subsequent leachate disposal.

(6) Ground water. It is necessary to define water levels, gradients, flow direction, and ground water chemistry in all water-bearing units in the vicinity of the landfill cover. Ground water investigations are usually performed during the RI phase. Typically, one or more wells are placed upgradient, and several wells are placed downgradient of the site. The wells are used to determine if the site is contaminating the ground water. Monitoring well data should be reviewed during the predesign phase to see if additional wells are needed. Monitoring wells will also be needed after construction to monitor the landfill cover's effectiveness.

(7) Foundation soils. The foundation soils should be characterized by determining material types and extent, water content, density, depth to ground water, etc. In addition, disturbed and undisturbed soil samples should be collected to determine specific geotechnical engineering properties. The type of sample and amount of material required is dependent on the type of test that will be performed. Typical geotechnical tests that are performed on foundation soils are discussed below in paragraph B-2*d*.

d. *Geotechnical laboratory requirements*. Geotechnical laboratory tests are required to assess the suitability of borrow sources and to establish soil properties for use in stability, settlement, and drainage analyses. Typical tests are described in the following paragraphs.

(1) Classification testing. Classification tests consist of sieve and hydrometer analyses, Atterberg limits, and moisture content testing. These tests are used to select borrow sites for cover materials and to design filter and drainage layers. Classification tests are also performed on the foundation soils beneath the landfill to determine if stability and settlement will be a concern.

(2) Standard or modified proctor. Proctor tests are performed to develop compaction criteria for cohesive soils.

(3) Relative density. Relative density tests are performed to develop compaction criteria for non-cohesive soils.

(4) Permeability. Permeability tests are typically performed on all barrier and drainage layer soils to establish their hydraulic conductivity (permeability).

(5) Density. Density tests are performed on foundation and borrow soils to establish the existing condition. For borrow soils, this information can be used to estimate swell and shrinkage potential due to excavation and compaction.

(6) Dispersive clay. This test is used to determine the erodibility of a soil. In a cover system, dispersive soils can result in excessive surface erosion or clogging of drainage layers.

(7) Consolidation. Consolidation testing is typically performed on foundation soils to estimate settlement resulting from placement of the landfill cover. Consolidation testing is normally not performed on the waste materials in the landfill because of the difficulty in obtaining representative samples.

(8) Shear strength. The shear strength of soils may be determined for use in stability analysis of the cover and/or foundation soils. Shear strength of the waste material is normally estimated because of the difficulty in obtaining representative samples.

(9) Direct shear tests. Direct shear tests should be performed on all potentially critical cover interfaces to determine interface friction values for use in stability analyses.

e. *Chemical data requirements*. Chemical testing is often required for the features listed below. A chemist should be involved in these aspects of the project.

(1) Landfill gas testing, control, and treatment.

(2) Borrow soil testing (contamination check).

(3) Leachate testing, control, and treatment.

(4) Ground water monitoring.

(5) Determination of landfill limits.

(6) Contaminated materials handling (regrading refuse).

(7) Disposal of contaminated site material.

(8) Decontamination water control, treatment, and disposal.

(9) Air monitoring during refuse regrading and normal operation and maintenance.

(10) Contaminated surface water runoff control during landfill regrading.

B-3. Cover System Components

a. *General*. The EPA technical guidance document entitled "Final Covers on Hazardous Waste Landfills and Surface Impoundments" (EPA/530-SW-89-047), provides design guidance on final covers for hazardous waste units. The design guidance presented in that document satisfies the requirements of 40 CFR 264 and 265. The EPA emphasizes that their recommendations are guidance only and not regulations. The EPA also acknowl-edges that other final cover designs may be acceptable, depending upon site-specific conditions and upon a determination by the EPA that an alternative design adequately fulfills the regulatory requirements. The following design considerations adhere to the EPA recommendations and reflect additional design requirements. As noted previously, the components of a hazardous waste landfill cover generally consist of a protective cover layer, drainage layer, low permeability layer, and a random fill layer overlying the waste. A gas collection system is also typically a component of the landfill cover.

b. *Protective cover layer - vegetative cover alternative*.

(1) General. The top layer of a cover system is comprised of an upper and lower component. The upper component is usually a vegetated cover; however, an armored surface may be applicable in some situations. The lower component is a layer of soil that is used to support the vegetative growth and to prevent freeze-thaw or other types of damage to underlying layers. The primary purpose of the vegetative cover is to resist wind and water erosion. However, the vegetative cover must also promote surface runoff, minimize infiltration of surface water, and maximize evapotranspiration. The vegetative cover will also function in the long term to enhance aesthetics and to promote a self-sustaining ecosystem on top of the cover.

(2) Design criteria. The selection of appropriate plant species is critical in establishing a vegetative cover. Grasses and low growing plants are most suitable and are available for most regions and climates. In contrast, trees, shrubs, and other woody vegetation are usually unsuitable because their deep root systems can damage the underlying layers. Planting during the appropriate season can also be critical to successfully establishing a vegetative cover. Guide specification CEGS-02935 should be used in the contract documents when specifying the vegetative cover component. According to EPA/530-SW-89-047, the vegetation component of the top layer should meet the following requirements:

(a) Locally adapted perennial plants.

(b) Resistant to drought and temperature extremes.

(c) Roots that will not disrupt the drainage and low-permeability layer.

(d) Capable of thriving in low-nutrient soil with minimum nutrient addition.

(e) Sufficient plant density to minimize soil erosion to no more than 0.45 kg/m^2/year (2 tons/acre/ year), calculated using the USDA Universal Soil Loss Equation. A higher erosion rate may be acceptable during the construction and vegetation establishment period. Otherwise, temporary erosion protection should be provided until the final cover is erosionally established.

(f) Capable of surviving and functioning with little or no maintenance.

(3) Revised Universal Soil Loss Equation (RUSLE). The RUSLE is a computer-based model incorporating more data and research since the formulation of the original Universal Soil Loss Equation. RUSLE was developed by the USDA Natural Resource Conservation Service.

c. Protective cover layer - armored cover alternative.

(1) General. As with the vegetative cover, the primary purpose of an armored cover is to resist wind and water erosion while promoting surface runoff to the greatest degree practical. An armored cover is used when a vegetative cover is inappropriate as the top component of the cover system. This would occur in climates that do not support vegetation or where other conditions, such as steep slopes, preclude the use of vegetation. An armored cover is typically comprised of very coarse materials such as crushed rock or cobbles. However, concrete, asphaltic cement, chemical sealants, or other materials may also be used. Riprap may also be required along the side slopes of the landfill if it is located in a flood plain.

(2) Design criteria. According to EPA/530-SW-89-047, the armored component of the top layer should meet the following requirements:

(a) Capable of remaining in place and minimizing erosion of itself and underlying soil components during extreme weather events.

(b) Capable of accommodating settlement of the underlying material without compromising the purpose of the component.

(c) Capable of maintaining the surface slope approximately the same as the underlying soil.

(d) Capable of controlling the rate of soil erosion from the cover to no more than 0.45 kg/m^2/year (2 tons/acre/year), calculated using the USDA Universal Soil Loss Equation. A higher erosion rate may be acceptable during construction. Otherwise, temporary erosion protection should be provided.

d. Protective cover layer - lower component. The composition of the lower component of the top layer is dependent on the type of upper component that will be utilized. When a vegetative cover is used, the lower component should consist of topsoil overlying select fill. In the case of an armored cover, topsoil is not required and the lower component will be comprised entirely of select fill. In either case, the EPA recommends that the lower component be composed of at least 600 mm (24 in.) of soil. A layer thicker than 600 mm (24 in.) may be required to prevent freeze-thaw damage to underlying layers or to increase the water storage capacity available to plants. General guidelines for the design of these alternatives are discussed in the following paragraphs.

(1) Topsoil.

(a) General. A relatively thin layer of topsoil is provided in the cover system to promote germination and plant root system development. Medium-textured soils such as loam soils have the best overall characteristics for seed germination and plant root system development. Sandy or coarse-grained soils are often a problem due to low water retention and loss of nutrients by leaching.

(b) Design criteria. Generally, the selected topsoil should have a pH value between 6.0 and 7.5 to ensure that the soil is not too acidic to sustain vegetation. In addition, topsoil should contain from 5 to

20 percent organic matter to promote and sustain plant growth through water retention and nutrient availability. Topsoil should be uniformly distributed and evenly s-pread over the select fill material to a minimum thickness of 150 mm (6 in.) with minimal compactive effort. The topsoil should also be contamination free and representative of soils in the vicinity that produce heavy growths of vegetation.

(2) Select fill.

(a) General. Below the topsoil layer or armored surfacing is the select fill layer. The purpose of the select fill is to provide a soil that is capable of sustaining the vegetative cover through dry periods and to protect the underlying geosynthetics and clay barrier layer from humans, animals, frost penetration, desiccation, and construction and maintenance equipment. The select fill also provides water holding capacity to attenuate rainfall infiltration to the underlying drainage layer. As with topsoil, select fill should consist of medium-textured soils, such as loams, for both function and constructibility. Cohesionless silts and sands are undesirable because these soils have low water retention capability and nutrients are easily leached from them. Clayey soil types are more fertile than sandy soils. However, high plasticity clays can damage underlying geosynthetics during placement. The best materials are cohesive but not highly plastic and include SC-SM (silty, clayey sand), SC (clayey sand), CL-ML (silty clay), and CL (lean clay) as classified by the Unified Soil Classification System (ASTM D 2487). Gap-graded soils should be avoided because they are susceptible to erosion.

(b) Design criteria. Material type and gradation requirements should be specified to prevent the use of highly plastic soils and to ensure compatibility with the underlying filter layer. In addition, a maximum particle size should be specified to protect against puncture or other damage to underlying geosynthetics. The maximum particle size specified will typically range from 9.5 mm (0.375 in.) to 25 mm (1 in.) depending on the type of geosynthetics present immediately beneath the select fill. The use of angular material should also be avoided because of increased potential for damaging geosynthetics. The ultimate choice of a select fill material will depend on the availability of economical borrow sources. The EPA recommends that the thickness of the select fill should be a minimum of 600 mm (24 in.) (including a minimum of 150 mm (6 in.) of topsoil if a vegetative cover is used) or equal to the maximum frost depth, whichever is greater. In addition, the final slope of the top of the landfill, after allowance for settling and subsidence, should be at least 3 percent. Constructibility issues are critical when placing select fill. Select fill should be placed starting at the toe and advancing up the slope. Placing fill in a top-down fashion can induce surface slope failures and tension in the underlying geosynthetics. The first layer of select fill should be placed in a loose lift 380 to 460 mm (15 to 18 in.) in thickness to protect the underlying materials. Only after the first layer of select fill has been placed should equipment be allowed on areas underlain with geosynthetics. Select fill should be placed on geosynthetics by dropping from a height no greater than 900 mm (36 in.). To further protect geosynthetics from damage, low ground pressure equipment should be utilized. Generally, traffic compaction via placement equipment is sufficient and will enhance the soil's ability to support vegetation. At no time should equipment be driven or pulled directly on top of any geosynthetic.

e. Filter layer - geotextile.

(1) General. A filter layer is normally required between the select fill and the underlying drainage layer. The filter layer ensures consistent drainage properties by preventing migration of fine-grained soil particles into the void spaces of the drainage layer below. For a landfill cover, the filter normally consists of a geotextile fabric; however, a series of graded granular materials could also be used. The majority of geotextiles used in cover systems are made from polypropylene or polyester polymers formed into woven and nonwoven fabrics. The design of a geotextile filter is dependent on a number of factors as discussed in the following paragraphs.

(2) Design criteria. Guide specification CEGS-02272 should be used in contract documents when specifying geotextiles for separation/filtration. Koerner (1990) provides detailed design information about the geotextile properties listed in the following paragraphs. Also, DeBerardino (1993a, 1993b) provides a summary of geotextile design procedures available.

(a) Soil retention. A geotextile filter must be designed to prevent the migration of soil particles from the select fill into the drainage layer. To accomplish this, the openings in the geotextile fabric must be small enough to retain the soil on the top side of the fabric. In the design of the geotextile filter, the coarser sized soil particles must be retained. Although some fines will initially pass through the filter, the coarse particles will eventually block further losses of finer particles if the soil is well graded. There are a number of methods available to evaluate the retention capability of a geotextile filter. All of these methods select an appropriate geotextile by comparing the particle size distribution of the soil to a fabric's opening sizes. Soil particle size is often represented by the percent passing a specific sieve size. For example, the term D_{85} refers to the sieve size which will allow 85 percent of a soil sample to pass. The opening size distribution of a geotextile is often represented by the percent of a given particle size that will be retained by a geotextile. For example, O_{95} indicates that a geotextile will retain 95 percent of a given particle size. Geotextile design methods also differ depending on other criteria such as whether the soils are cohesive or noncohesive, if the fabric is woven or nonwoven, soil gradation, etc. The designer should select a method that is well documented, has proven to be reliable, and is appropriate for site specific conditions. AASHTO-ABC-ARBTA Task Force Number 25 Specification for Geotextiles provides the following guidance: For soils with 50 percent or less particles by weight passing U.S. No. 200 sieve, apparent opening size (AOS) should be less than 0.6 mm (greater than U.S. No. 30 standard sieve). For soils with more than 50 percent particles by weight passing U.S. No. 200 sieve, AOS should be less than 0.297 mm (greater than U.S. No. 50 standard sieve). AOS and O_{95} are equivalent terms.

(b) Cross-plane permeability. The design of the geotextile must allow an adequate flow of water from the select fill through the filter to the drainage layer. Consequently, the design must ensure that the cross-plane permeability of the geotextile is greater than the vertical permeability of the overlying select fill by some factor of safety. Depending on the method selected, the factor of safety can range from 1 to over 10. Because of the thick compressible nature of some geotextiles, a permittivity value for the geotextile is often specified by the manufacturer. Permittivity is defined as the volumetric flow rate of water per unit cross-section area, per unit head, under laminar flow conditions, in the normal direction through the fabric. In design, a required permittivity value for the geotextile is determined based on the flow capacity of the select fill layer.

(c) Clogging (long term compatibility). In addition to meeting the soil retention and permeability requirements, the geotextile should continue to allow sufficient cross plane flow even if a percentage of the pores become clogged during the life of the system. For filters used in cover applications, clogging is usually a result of soil particles embedding in the open spaces of the fabric. Although generally not a problem in landfill covers, chemical and/or biological clogging could also occur if the filter is exposed to leachate or high pH liquids. There have been a number of empirical methods developed to evaluate the clogging potential of a filter fabric. If necessary, the long term compatibility of the fabric can be directly determined by evaluating the select fill and geotextile filter in the laboratory using the gradient ratio test as described in American Society for Testing and Materials (ASTM) Test Method D 5101, Measuring the Soil-Geotextile System Clogging Potential by the Gradient Ratio. Clogging potential can also be evaluated using ASTM D 1987, Biological Clogging of Geotextiles or Soil/Geotextile Filters.

(d) Survivability. Survivability refers to the ability of the fabric to withstand the construction/ installation process. Items that should be considered include the type of construction equipment, construction technique, and subgrade material. The index tests commonly referred to as the survivability criteria for geotextiles are puncture (ASTM D 4833), grab tensile strength (ASTM D 4632), and trapezoidal tear strength (ASTM D 4533). The American Association of State Highway and Transportation Officials AASHTO-ABC-ARBTA Task Force No. 25 and other organizations have published recommended minimum values for these and other tests that are intended to minimize the potential for construction damage. It is also essential that proper construction techniques are specified and used to ensure that the filter will not be damaged during construction.

(e) Strength. In some cases, the geotextile fabric in the cover may be in tension as a result of inadequate sliding resistance at material interfaces. Tensile and biaxial stresses may also occur in the geotextile as a result of differential settlement. In these situations, the fabric should have adequate strength to withstand these tensile stresses. ASTM D 4632 should be used to specify geotextile strength. Elongation (ASTM D 4632) is another design consideration for geotextiles. Geotextiles with a percent elongation at break of less than 50 percent should have higher strength requirements for puncture, grab tensile, and trapezoidal tear strength as shown in AASHTO M 288-92. Nonwoven geotextiles typically have elongations of 50 percent or greater at break while the elongation at break for woven geotextiles is typically less than 50 percent.

(f) Sewn seams. Both sewn and overlapped seams are used for landfill cover geotextiles. A flat seam using a two thread chain stitch is often used for filtration geotextiles. For geotextiles placed in tension, stronger and more complex seams are specified. Alternatively, a minimum seam strength per ASTM D 4884 or ASTM D 4595 could be specified. Heat bonding and overlapping are other potential methods of joining geotextiles. However, where the design requires the geotextile to resist tensile stress, seams should be sewn. The contract documents should indicate which seams must be sewn. Field seam testing is often not performed for geotextiles used for filtration and separation. However, testing should be performed if the geotextile will be in tension.

(g) Overlapped seams. For overlapped seams, a 300-mm (12-in.) overlap should be the minimum requirement in all cases. Table 3 of AASHTO M 288-92 provides additional guidance on overlap requirements.

f. Filter layer - granular filter.

(1) General. Design criteria for granular filters are largely empirical and are given in terms of characteristic particle sizes (D_{15}, D_{85}, etc.). Engineer Manual (EM) 1110-2-1913 specifies that a granular filter must meet three requirements: piping or stability, permeability, and sufficient discharge capacity if the filter is also used as a drain. In some cases, it may be necessary to design a multiple layered or graded filter to meet these requirements. For severely gap-graded soils, the design of a filter using standard empirical relationships may not be appropriate. In these cases, it may be necessary to perform filtration tests.

(2) Design criteria.

(a) Piping or stability. Filters allow seepage to move out of a protected soil more quickly than the seepage moves within the protected soil. Thus, the filter material must be more open and have a larger grain size than the protected soil. To prevent the movement of erodible soils and rocks through filters, the pore spaces between filter particles should be small enough to hold some of the larger particles of the protected material in place. These larger sized particles will eventually block finer soil particles from migrating through the filters if the soils are well graded. EM 1110-2-1913 (Appendix D), provides tables and equations for designing filters to prevent piping.

(b) Permeability. The design of the filter must assure that the filter material is much more permeable than the material being drained. EM 1110-2-1913 (Appendix D), provides the following guidance for the permeability criterion. The requirement that seepage move more quickly through the filter than through the protected soil is met by comparing the D_{15} size of the filter to the D_{15} size of the protected soil. If the D_{15} of the filter is at least 5 times greater than the D_{15} of the soil, the filter will be approximately 25 times more permeable than the protected soil. The criteria listed above defines a wide range or band of gradations that will satisfy the design requirements. The gradation that is specified should fall within this band, be approximately parallel to the gradation curve(s) of the protected soil, and reflect materials that are available.

g. Drainage layer - geonet.

(1) General. The function of the drainage layer in a landfill cover is to intercept water that percolates through the top layer of the landfill cover, reduce the hydraulic head on the underlying barrier layer, and to enhance slope stability by reducing seepage in the cover system. Drainage layers are also used in landfill covers for gas collection and collection of horizontally flowing liquids escaping from the landfill. Drainage layers used in landfill covers to intercept percolating water should be designed to minimize the time that water is in contact with the low-permeability layer. The drainage layer usually consists of a drainage blanket and a collection/ transportation system. A complex collection/ transportation system might incorporate a series of collectors, laterals, and main lines to direct and dispose of water entering the drainage system. The drainage blanket in a landfill cap is generally constructed with either geonets or granular materials. Geonets are unitized sets of parallel plastic ribs positioned in layers such that liquid can be transmitted within their void spaces. Often, a geotextile will be attached to one or both sides of the geonet by the manufacturer. Geonets have replaced granular materials as the most commonly used type of drainage media because they require less space and are easier to construct. Most commercially available resins used for geonets are polyethylene. The final compound is approximately 97 percent polyethylene with 2-3 percent carbon black added for U.V. resis-tance. An additional 0.5-1 percent additives are added as antioxidants and

processing aids. Geonets typically range from 5.0 to 8.0 mm (0.20 to 0.30 in.) in thickness but can be considerably thicker. According to EPA/530-SW-89/047, geonets may be used if it can be shown that they are at least equivalent to the EPA's recommended granular system in hydraulic transmissivity and longevity.

(2) Design criteria. Guide specification CEGS-02273 should be used in contract documents when specifying geonets. According to EPA/530-SW-89/047, a geonet drainage layer should meet the following requirements:

- Same minimum flow capacity as a granular layer in the same situation; hydraulic transmissivity no less than 3×10^{-5} m^2/sec under anticipated overburden for the design life.

- Inclusion of a geosynthetic filter layer above the drainage material to prevent clogging by the overlying top layer of soil.

- Inclusion of geosynthetic bedding beneath the drainage layer, if necessary, to increase friction and minimize slippage between the drainage layer and the underlying geomembrane and to prevent intrusion of the geomembrane into the geonet drainage layer.

(a) Compatibility. Chemical compatibility between infiltrating surface water and the geonet is generally not critical and does not require compatibility testing. However, if a geonet drainage layer is used to intercept leachate exiting the landfill side slopes, the chemical resistance of the geonet to the leachate may need to be evaluated.

(b) Compressive strength. The flow capability of a geonet is reduced as it deforms under compressive loads. Consequently, a geonet must be designed to withstand compressive loads. For landfill covers, the normal stresses imposed on a geonet from overlying fill material and live loads from construction equipment are usually small and not critical to the performance of the system.

(c) Flow capability. The geonet flow capacity requirements are determined from a site-specific water balance model. The Hydrologic Evaluation of Landfill Performance (HELP) model is the most often used model to estimate flow requirements for geonets. The planar flow rate, or transmissivity, of geonets is determined using ASTM D 4716, Constant Head Hydraulic Transmissivity (In-Plane Flow) of Geotextiles and Geotextile Related Products. Laboratory tests should reflect the normal load and hydraulic gradient expected in the field. The type of material in contact with the geonet can also affect the flow properties of the geonet and should be considered when evaluating transmissivity test data. The transmissivity determined in the laboratory should be adjusted if the test setup does not realistically reflect expected field conditions. The adjustments, in the form of factors of safety, should account for:

- Elastic deformation or intrusion of the adjacent geosynthetics into the geonet's core space.

- Creep deformation of the geonet and adjacent geosynthetics into the geonet's core space.

- Chemical clogging and/or precipitation of chemicals in the geonet's core space.

- Biological clogging of the geonet's core space.

(d) Minimum slope. According to the guidelines in EPA/530-SW/89-047, the slope of the drainage layer after settlement must be 3 percent or greater.

(e) Pressure Head in Select Fill. The drainage layer should be designed to prevent head build-up in the overlying select fill.

(f) Tensile strength. Usually geonets are not designed to carry tensile stresses. However, if tensile stresses are anticipated, due to slippage at material interfaces or large amounts of differential settlement, tensile strength requirements for the geonet and geonet connectors should be specified.

h. Drainage layer - granular.

(1) General. Granular materials can also be used to construct the drainage layer. The design of a granular drain is similar to the design of a geonet.

(2) Design criteria. According to EPA/530-SW-89/047, a granular drainage layer should meet the following requirements:

- Minimum thickness of 300 mm (12 in.) and minimum slope of 3 percent at the bottom of the layer; greater thickness and/or slope if necessary to provide sufficient drainage flow as determined by site-specific hydrologic modeling.

- Hydraulic conductivity of drainage material should be no less than 1 x 10^{-2} cm/sec (hydraulic transmissivity no less than 3 × 10^{-5} m^2/sec at the time of installation).

- Granular material should be no coarser than 9.5 mm (0.375 in.), and classified as sand-poorly graded (SP); it should be smooth and rounded and should contain no debris that could damage underlying geosynthetics, nor should it contain fines that reduce permeability.

- A natural or geotextile filter should be provided to prevent clogging of the drainage layer.

i. Collection/transportation system.

(1) General. Once the physical characteristics of the drainage blanket have been determined, a system for allowing the collected water to exit from beneath the cover must be designed. The collected water can be allowed to flow out through a gravel drainage layer, or a pipe collector system can be used. The pipe collector system is typically used because it is more resistant to clogging.

(2) Design criteria. Perforated polyvinyl chloride (PVC), smooth walled high density polyethylene (HDPE), or corrugated HDPE pipe are typically installed around the perimeter of the landfill to collect flow from the drainage layer. The maximum flow which this system will be required to carry can be determined from the HELP Model using the peak daily flow determined for the lateral drainage layer. Since the collector pipe will be non-pressurized, Manning's formula for open channel flow can be used for sizing the pipe. A 150-mm- (6-in.) diam pipe is typically the minimum size pipe used for drainage systems to allow easy maintenance. The calculated flow capacity of a 150-mm- (6-in.) diameter pipe will generally exceed the required capacity based on hydraulic considerations. Laterals carry flow from the collector system out from beneath the landfill cover. The lateral spacing can be calculated using Manning's equation to determine the maximum allowable flow of the collector pipe and then spacing the laterals accordingly. Laterals are typically made of non-perforated PVC or HDPE and are spaced no more than 183 m (600 ft) apart for ease of inspection and monitoring purposes. Also, if a section of the drainage pipe fails, frequently spaced laterals lessen the consequence of the failure.

Manning's Equation:

$$Q = (a)\left(\frac{1.00}{n}\right)(R^{0.67})(S^{.5})$$

where

Q =
flow in pipe (cubic meters/second)

a =
cross-sectional area of pipe (square meters)

n =
pipe roughness coefficient

R =
hydraulic radius = $\frac{\text{area in flow (square meters)}}{\text{welled perimeter (meters)}}$

S = slope of pipe

(a) Perforations. EM 1110-2-1901 provides guidance on sizing perforations for preventing infiltration of material into the perforated pipe:

$$\frac{\text{50 percent size of filter material}}{\text{hole diameter or slot width}} \geq 1.0\text{(holes) or} \geq 1.2\text{(slots)}$$

(b) Pipe material requirements. No Corps of Engineers guide specifications are available for plastic pipe. EPA/600/R-93/182 should be referred to when specifying plastic pipe. There is an AASHTO specification available for corrugated polyethylene pipe in the 75- to 250-mm- (3- to 10-in.) diam range under the designation of M 252-90 and another for 300- to 900-mm- (12- to 36-in.) diam pipe under the designation of M 294-90.

j. Low permeability layer - geomembrane.

(1) General. The objective of the low permeability layer is to minimize migration of liquids through the hazardous waste. This layer should also have a permeability less than or equal to the permeability of the bottom liner system or natural subsoils present. In general, the EPA has interpreted this to mean that the cover should contain a geomembrane/ soil composite layer similar in concept (but not necessarily identical construction materials) to a composite double liner system for landfills and surface impoundments. Geomembranes are thin sheets of flexible, relatively impervious, polymeric materials whose primary function is to act as a barrier to liquids and vapors. The polymeric materials are manufactured into sheets

and transported to the job site, where placement and field seaming are performed.

(2) Design criteria. The most common types of geomembranes currently being used for landfill covers are PVC and polyethylene with polyethylene being the most commonly used geomembrane on Corps of Engineers jobs to date. A minimum thickness of 1.0 mm (40 mils) is often specified for cover geomembranes due to constructibility concerns. Polyethylene geomembranes can be manufactured with textured surfaces which improve the frictional resistance at adjacent interfaces. Textured geomembranes should only be considered for slopes greater than or equal to 1V on 4H. In general, textured geomembranes are more expensive, have diminished physical properties, have potentially more manufacturing defects, and are more difficult to field seam and inspect than non-textured geomembranes. Guide specification CEGS-02271 should be used in contract documents when specifying geomembranes. "Designing with Geosynthetics" (Koerner 1990) provides a detailed summary of geomembrane design considerations. EPA/600/R-93/182 summarizes construction quality assurance and quality control issues which should be considered when using geomembranes.

k. *Low permeability layer - clay*.

(1) General. The purpose of the clay barrier layer in a composite cover is to inhibit the movement of water which passes through holes in the geomembrane. Soils used for the clay barrier layer are selected to meet a specific hydraulic conductivity requirement (typically 1×10^{-7} cm/sec). The designer needs to ensure that a sufficient amount of suitable soil is available for the clay barrier layer and specifications are written so that the soil is properly placed, compacted, and protected. If soils found in the vicinity of the project do not contain a sufficient amount of clay to be suitable for direct use, a common practice is to blend available natural soils with bentonite. Clay barrier layers are normally a minimum of 600 mm (24 in.) in thickness. Freeze-thaw cycles will increase the permeability of a clay layer. Therefore, the cover should be designed so that the clay layer is located below frost depth.

(2) Design criteria. Guide specification CEGS-02443 should be used in contract documents when specifying low permeability clay layers. The process of selecting soils and verifying their suitability varies from project to project. Locating a clay borrow source can take place during the design process, or it can be left up to the contractor. If locating and testing a borrow source is left up to the contractor, the designer should verify that acceptable borrow sources exist in the area during the design phase. In general, the testing and quality control steps required for construction of a low permeability clay layer are as follows:

- A potential borrow source is located and explored to determine the vertical and lateral extent of the source and to obtain representative samples for testing.

- Once construction begins, quality control (QC) and quality assurance (QA) tests are performed to confirm the suitability of materials being used.

- After a lift of soil has been placed, additional tests are performed to verify the soils are being placed and compacted properly.

(3) Borrow assessment testing. EPA/600/R-93/182 describes the required properties of a low permeability borrow soil. Borrow source assessment testing can be performed during the design or construction phase. It is done to determine the properties of potential borrow soils. Tests should be performed on each principal type or combination of materials proposed for use to assure compliance with specified physical properties and to develop compaction requirements for placement. At a minimum, one set of borrow assessment tests should be performed for each borrow source proposed. A set of tests should consist of classification, moisture-density (compaction), and hydraulic conductivity testing.

(a) Classification testing. Test pits or borings should be placed in a grid pattern to characterize each proposed borrow source. Small samples obtained from borings are excellent for index property testing but often do not provide a very good indication of subtle stratigraphic changes in the borrow area. Test pits excavated into the borrow soil with a backhoe or other excavation equipment can expose a large cross section of the borrow soil, providing a much better idea of the variability of soil than viewing small soil samples obtained from borings. Soils should be grouped into "principal types" based on visual classification by a qualified geologist or geotechnical engineer. Classification testing should be performed on representative samples of each principal type or combination of materials. At a minimum, one set of classification tests should be performed per 5,000 cu m (6,500 cu yd) of proposed borrow. Classification testing should consist of moisture content, liquid and plastic limits, and particle size analysis.

(b) Compaction testing. One of the most important aspects of constructing a low permeability clay barrier layer is proper remolding and compaction of the soil. The traditional method of specifying the "acceptable zone" of moisture contents and densities has been based on achieving adequate strength and limiting compressibility. This method is not ideal for clay layers designed to achieve low permeabilities. One satisfactory approach to developing moisture/ density criteria for a low permeability clay layer is shown below. The same general procedure may also be used for soil-bentonite mixtures. The procedure is as follows:

- For each soil type to be used in the clay barrier layer, prepare and compact samples with modified (ASTM D 1557), standard (ASTM D 698), and reduced compaction procedures to develop compaction curves. The "reduced compaction" procedure is identical to the standard compaction procedure except that 15 drops of the hammer per lift are used instead of the standard 25 drops.

- Based on compaction test results, specimens should be compacted to various densities and permeated using the test procedure described in ASTM D-5084. Confining pressures and hydraulic gradients used to perform this testing should be representative of landfill cover conditions.

- An acceptable zone should be developed which encompasses the moisture contents and densities which achieve the required permeability.

- The acceptable zone should be modified based on shear strength considerations.

l. Low permeability layer - geosynthetic clay liner.

(1) General. Geosynthetic clay liners (GCLs) are factory manufactured hydraulic barriers consisting of bentonite clay materials supported by geotextiles or geomembranes. GCLs are used to augment or replace compacted clay layers or geomembranes. All of the GCL products available in North America use sodium bentonite clay powder or granules with a mass per unit area in the range of 3.2 to 6.0 kg/m^2 (0.66 to 1.2 lb/ft^2). The clay thickness of the products vary between 4.0 to 8.0 mm (160 to 320 mils). GCLs are available in widths of 2.2 to 5.2 m (7 to 17 ft) and lengths of 30 to 60 m (100 to 200 ft). GCLs are most often considered for use where there is a limited supply of natural clay or limited landfill space. GCLs are also less susceptible to the effects of desiccation and freeze/thaw than natural clay layers. This is a significant issue for landfill covers since the low permeability layer is located so close to the surface of the landfill.

(2) Design criteria. EPA/600/R-93/171, "Report of Workshop on Geosynthetic Clay Liners," summarizes much of the available information on GCLs. Guide specification CEGS-02442 should be used in contract documents to specify material and installation requirements for geosynthetic clay liners.

m. Gas collection and removal system.

(1) General. Landfill gas production results from vaporization, chemical reactions and biological decomposition. Biological and chemical degradation of organic waste materials is the predominant source of landfill gas. Degradation of organic materials results in the production of carbon dioxide (CO_2) and methane (CH_4). Other gases will also be generated depending on the composition of the waste. Factors affecting gas production are given in Table B-1. Gas migration occurs by two processes, convection and diffusion. Convection is gas flow induced by pressure gradients. Convection is also induced by buoyancy forces since gases such as methane are lighter than air. Gas flow by diffusion is induced by

Table B-1
Factors Affecting Gas Production

Mechanism	Factor
Vaporization	- Vapor pressure of gases present - Gas concentrations at the liquid-air interface - Temperature - Confining pressure
Chemical Reaction	- Composition of waste - Temperature - Moisture content
Biological Decomposition	- Nutrient availability for bacteria - Refuse composition - Age of landfill - Moisture content - Oxygen availability - Biological inhibitors - Temperature - pH

concentration gradients resulting from gas production. Vertical or lateral migration paths for gas movement out of the landfill are influenced by the presence of migration corridors and/or barriers. Migration corridors include sand and gravel lenses, void spaces, cracks, fissures, utility conduits, drainage culverts, and buried lines. Barriers to gas migration include clay layers, geomembranes, geologic formations, and high or perched water tables. The potential impacts of landfill gas are as follows:

- Explosion hazard. Methane can migrate through the subsurface and collect in adjacent structures creating a potential explosion hazard.

- Vegetation distress. Landfill gases can distress the vegetation on a landfill cover.

- Odor. Odor control becomes a design parameter if the landfill is located adjacent to existing or potential developments.

- Physical disruption of cover components. Gas buildup beneath the geomembrane can force the geomembrane to protrude or “bubble out” from the cover. Landfill gases can also cause desiccation cracking on the underside of the clay layer resulting in an increase in permeability.

- Toxic gases. Gases produced by landfills can be toxic or may not comply with regulatory requirements.

(2) Design of gas control systems. Gas control systems consist of collection, conveyance, and outlet components and are designed to be either passive or active. A passive system allows the landfill gas to exit the collection system without mechanical assistance whereas an active system utilizes mechanical assistance, such as blowers, to extract gases. Depending on the potential impacts of the landfill gas and local regulatory criteria, gases are either dispersed into the atmosphere or collected and treated. All components of the gas control system must consist of materials that are compatible with the landfill gas. Typical gas control systems are described below. This ETL discusses collection systems and conveyance piping. Gas treatment systems for the collected gas are not covered.

(a) Continuous blanket systems. The EPA recommends that a continuous blanket gas collection system consist of a minimum of 300 mm (12 in.) of granular fill or an equivalent geosynthetic material located below the impermeable barrier layer. Equivalence is based upon the ability of the geosynthetic material to efficiently remove gases produced, resist clogging, withstand expected overburden pressures, and function under the stresses of construction, operation, and future deformation of the waste. Perforated horizontal collection pipes are incorporated into the design of systems using granular collection blankets. Vertical outlet pipes transport the collected gases from beneath the landfill cover. Blanket systems can be either passive or active. Once placed, the granular material should allow free movement of gases to collection and outlet pipes. Geotextile filter layers may also be required to prevent clogging of the gas collection layer. The vertical outlet pipes for passive systems need to be located at the highest elevations of the collection blanket to allow maximum evacuation of gas. The number of vent pipes should be minimized and are normally spaced about 60 m (200 ft) apart. This provides approximately one vent per 4,000 m^2 (1 per acre).

(b) Well systems. Well systems consist of a series of gas extraction wells (perforated or slotted vertical collection pipes) that penetrate to near the bottom of the refuse. The components of extraction wells are usually similar to that of standard ground water monitoring wells (i.e. riser, screen, gravel pack). A well extraction system, either active or passive, is useful for layered landfills where vertical gas migration is impeded. The design of a vent well system requires estimates of the rate of gas production and the radius of influence of the wells. EPA 450/3-90-011a provides design guidance for active and passive well systems. However, due to the variability of landfill refuse, design procedures are difficult to apply to gas collection systems. Gas collection wells are typically spaced at a frequency of one per acre.

(c) Monitoring probes. Gas monitoring probes are used in conjunction with both active and passive systems to detect landfill gases migrating off-site. Monitoring probes are similar in construction to gas extraction wells. A typical configuration of a monitoring probe is shown in EPA 450/3-90-011a. Probes are typically placed around the perimeter of the landfill at a spacing of 150-300 m (500-1,000 ft). However, probe placement is site specific. At some sites, they are used only where there are nearby buildings and are closely spaced between the landfill and the buildings. The tips of the probes should be placed in pervious strata above the water table which are likely to provide a flow path for the landfill gas.

(d) Well heads and header piping. Well heads for passive extraction systems typically consist of a U-shaped pipe to prevent precipitation from entering the well. Well heads for active collection systems may include sampling ports, pressure gauges, control valves, and flexible connections. Header piping is used for active systems to transport gas from the collection system to a flare. The header piping is typically made of PVC or HDPE and should be sized to provide for minimal head losses and additional capacity, should supplementary extraction wells be required at a later date. The piping can be placed on the landfill surface or buried beneath the surface. The advantage of placing the header pipe on the landfill surface is ease of maintenance. However, this type of installation will result in exposure of the piping to UV radiation and an increased potential for damage from maintenance equipment and vandalism. The potential for blockage due to condensate freezing in the pipes is also increased if the header pipe is placed on the landfill surface. If the header pipe is buried within the landfill cover, it is typically located above the geomembrane cover system but below frost depth. A minimum of 150 mm (6 in.) of bedding material should be placed over the geomembrane prior to placement of the header pipe. Condensate storage tanks should be located at low points in the header pipe system to prevent blocking of the pipe with condensate. Corrugated metal protective sleeves are often used where the header pipe crosses beneath access roads.

n. *Random fill and regraded refuse*.

(1) General. Random fill is used as the foundation layer for overlying cover materials and to establish slopes for drainage. In some situations, wastes can be graded to help establish slopes for drainage. The thickness of random fill will be dictated by settlement, stability, and drainage requirements. Most soils are suitable for use as random fill. Therefore, the ultimate selection of a random fill is usually based on local availability of materials. Materials which may be unsuitable for use as random fill include debris, roots, brush, sod, organic or frozen materials and soils classified (according to ASTM D 2487) as PT, OH, or OL. However, site debris and other materials are sometimes placed in the random fill zone if they will not create settlement problems. Generally, these materials are placed as low as possible in the random fill zone.

(2) Placement criteria. The random fill layer should be a minimum of 300 mm (12 in.) thick to provide a foundation to allow adequate compaction of the low-permeability clay layer. Typically, random fill is placed in lift thicknesses of 200 mm (8 in.) for cohesive materials and 300 mm (12 in.) for cohesionless materials. Specific compaction requirements (density) are often not used for the bottom lifts of the random fill because of the soft compressible nature of the underlying refuse. For these lower layers, a procedure specification should be used that identifies the minimum number of passes of a specific type of compaction equipment. Compaction requirements for the upper layers of random fill are typically determined by the standard proctor test (ASTM D 698). Random fill is typically compacted to a minimum of 90 percent of maximum density.

(3) Refuse excavation. In certain circumstances, limited excavation and reshaping of the landfill surface can minimize the volume of random fill required, resulting in substantial cost savings. If refuse excavation is required, the excavated refuse material must be regraded and located under the random fill bedding layer. The refuse should be recompacted in 300-mm (12-in.) layers with a minimum of five passes of a standard municipal landfill trash compactor. When regrading refuse, 150 mm (6 in.) of daily cover is normally required to control vectors and odors. Surface runoff control measures are also needed to

assure receiving streams are not contaminated should a rain event occur during regrading operations. Excavation into refuse materials may expose unknown landfill contents such as buried drums, medical waste, unexploded ordnance, nuclear waste, or bulky debris. Consequently, excavation into the landfill requires specific safety and health considerations such as spark free grading equipment, air monitoring, and personnel protective equipment (PPE). The level of PPE will be determined on a site-specific basis. Level B PPE may be required if hazards are unknown.

B-4. Geotechnical Design

a. *Settlement*.

(1) Results of settlement. Excessive total or differential settlement of the cover system can have the following result:

- Increased permeability of the clay layer due to cracking.
- Slope instability due to steepened side slopes.
- Geomembrane or other geosynthetic failure due to tensile stresses.
- Cover penetration connection (e.g., gas vent pipe boots) failures due to the development of stress concentrations.
- Internal drainage layer and surface drainage disruption due to changes in design slopes.
- Leachate or gas collection system disruptions due to changes in design slopes.
- Ponding and increased infiltration.

Settlement of the cover system is the result of consolidation of both the refuse material and the foundation soils. Settlement is due to relocation of soil particles and landfill debris, physical-chemical changes from corrosion and oxidation, and bio-chemical decomposition. The magnitude of settlement is dependent on a number of factors including the following:

- Thickness of refuse.
- Type of refuse (e.g., construction debris and municipal wastes).
- Density or void ratio of refuse.
- Amount of decomposable materials.
- Leachate levels.
- Environmental factors such as precipitation and temperature.
- Ground water conditions.
- Weight of final cover.
- Type of foundation soils.
- Stress history (landfill operational history).

It is important to note that many sites require a combination of remedial technologies. For example, ground water pump and treat systems are often used in conjunction with final covers. If pump and treat systems are part of the remedial action, the effect of lowering the water table needs to be considered in the settlement analysis. Lowering the water table will create higher effective stresses in the previously saturated strata which may result in a greater degree of consolidation of these soils and larger settlement of the landfill cover.

(2) Design criteria.

(a) Refuse settlement analysis. Mechanical settlement, due to the placement of the landfill cover, occurs rapidly and is typically complete in several weeks. Mechanical settlement is a function of the compressibility of the waste and is related to the waste's void ratio. The combination of mechanical secondary compression, physical/chemical action, and biochemical decay causes settlement to continue with time. The method of settlement analysis typically used for landfills comes from a method presented by Sowers (1973). EPA/600/52-87/025 and EPA/600/2- 85/035 provide additional technical information on the settlement of landfill covers. Settlement of a landfill should be determined across several sections which are considered representative of the landfill to determine if adverse impacts are expected as a result of settlement. A method for determining the stresses in geosynthetic fabrics resulting from differential settlement is presented in EPA/625/4-91/025, Design and Construction of RCRA/CERCLA Final Covers.

(b) Foundation settlement analysis. If the natural foundation material under the waste fill is composed of fine grained soils such as soft clays, foundation consolidation will contribute to the overall settlement of the final cover. Traditional settlement analyses based upon site specific soil characteristics and loading conditions should be used to estimate foundation settlement. EM 1110-1-1904 provides detailed information on performing settlement analyses.

(c) Settlement design considerations. Prior to the placement of random fill material, the landfill surface must be cleared of vegetative cover and proof-rolled to reduce settlement. Compaction equipment 18,000 to 32,000 kg (40,000 to 70,000 lb) in weight is often used for proof rolling. The greatest effect from this equipment results from the initial 8 to 12 passes. Resilient materials such as old tires do not densify under any amount of rolling. When settlement of either the waste fill or the foundation is expected to be excessive, preloading (or dewatering) can be used to minimize post-construction settlement. After preloading is complete, the surcharge fill can be reshaped as the random fill layer.

b. Stability analysis.

(1) General. Potential stability problems for a landfill cover could result from the foundation soil, the refuse, or at cover material interfaces. The stability of a landfill is controlled in broad terms by the following factors:

- The properties of the foundation soil.
- The strength characteristics and weight of refuse.
- Inclination of slopes.
- Leachate levels and movements within the landfill.
- Frictional resistance of cover material interfaces.
- Cover resistance to erosion.

Quantification of the geotechnical properties of waste materials is very difficult; therefore, geotechnical investigations of these materials is rarely undertaken. Also, design procedures and guidance have not kept pace with the rapid increase in the use of geosynthetics in landfill covers. The following stability issues should be addressed during design.

(2) Design criteria.

(a) Cover component interfaces. The stability of geosynthetic interfaces normally controls the design of side slopes of a cover rather than the stability of the waste fill or foundation. Cover component stability is assessed by analyzing the frictional resistance between each adjacent layer. EPA/625/4-91/025 describes procedures for analyzing the stability of cover systems and determining strength requirements for reinforcement materials. Typical interface friction angles between adjacent geosynthetics or between the geosynthetics and adjacent soils range from 8 to 25 degrees. Because of this large variation in friction angles, it is important to have a requirement in the specifications that the Contractor perform interface friction tests on the actual project materials and submit the results to the designer for approval. Interface friction values should be determined using samples of the materials to be used for construction. Placement, loading, and wetting conditions used during testing should also be representative of field conditions. ASTM D 5321 describes the procedure used to perform interface friction tests. Reinforcement layers can be incorporated into the design to prevent tensile forces from developing in the geosynthetic components of the cover. Typically, geotextiles or geogrids are used for this purpose. When reinforcement layers are utilized, the material must have sufficient tensile strength and must be properly anchored. Benches on the landfill cover can also be used to provide additional stability for the cover system.

(b) Factor of safety for cover interfaces. Typically, a minimum factor of safety of 1.5 should be used for static conditions. This value may need to be increased in seismically active areas. If possible, friction testing should be conducted during design using site-specific materials and anticipated field conditions. Where this is not possible, frictional resistance values should be selected for design calculations based on tests performed by others which are similar to conditions anticipated in the field.

(c) Waste fill mass and foundation stability. After the slopes are preliminarily selected based on cover component interface stability, the overall stability of the waste fill mass and foundation needs to be analyzed. As noted previously, the geotechnical characteristics of refuse material are extremely difficult to determine. The mechanical behavior of refuse is typically expressed in terms of an apparent friction angle and a cohesion intercept. These parameters are back-calculated from actual cases of failure or cases where large deformations in refuse have occurred. They can also be conservatively estimated by observing existing refuse slopes and then back-calculating to determine the strength parameters assuming a factor of safety of 1.0. It should be noted that refuse material can be highly variable. The text entitled "Geotechnical Practice for Waste Disposal" (Daniel 1993) provides estimates of waste strength parameters. Additional information on properties of waste fill materials can be found in ASTM STP 1070 (Morris and Woods 1994). Strength parameters used for the foundation soils are usually determined through field sampling and laboratory testing. Seismic considerations should also be addressed where applicable. Computer program UTEXAS3 is typically used to perform stability analyses for landfills. Edris and Wright (1992) provides information on the use of UTEXAS3.

(d) Waste fill mass and foundation factor of safety. Recommendations for minimum factors of safety for slope stability analyses can be found in the document entitled "Guide to Technical Resources for the Design of Land Disposal Facilities" (EPA/625/6-88/018). If the designer is confident of strength parameters, a safety factor of 1.25 is recommended where there is no imminent danger to human life or to the environment if the slope fails. The safety factor should be increased to 1.5 when strength values are uncertain. When there is imminent danger to human life or if there would be a major environmental impact if the slope failed, the minimum factor of safety should be 1.5 or greater.

(e) Other stability issues. In addition to the items presented above, there are a number of other factors that should be considered during design. These include the effects of surface water and leachate seepage forces, desiccation cracking, seismic conditions, freeze/thaw effects, construction stresses, and long-term stress relaxation of reinforcement geosynthetics.

c. Test fills.

(1) General. A test fill is sometimes constructed prior to full scale construction of the landfill cover for the following reasons:

- To evaluate cover stability.
- To ensure the as-built cover meets the performance objectives.
- To verify geosynthetics are not damaged during construction.
- To conduct large scale permeability tests using sealed double ring infiltrometers.
- To determine material placement criteria.

(2) Design criteria. Test fills are often constructed on the steepest slope of the landfill cover. They should be a minimum of three times the width of the compaction vehicles. Widths are typically 10-15 m (30-50 ft). Lengths should be sufficient to allow equipment to reach proper operating speed for a minimum of 8 m (25 ft). Test fills are typically 20-30 m (65-100 ft) long. The materials, construction procedures, and test procedures should be as specified for full scale construction of the landfill cover. Before beginning construction, the Contractor should be required to construct drainage controls to divert surface runoff around the test fill.

(a) Testing. Density, moisture content, classification, and permeability tests should be performed on each lift of the test fill clay layer. Shelby tubes used to collect permeability samples should also be examined to determine if good interface bonding has occurred between lifts of the clay layer. Geomembrane seams can be destructively tested for strength and non-destructively tested for leaks. Seams for geotextiles and geogrids should be tested if they will be required to carry tensile loads. Tests should be required on other components of the test fill, as needed, using test procedures outlined in the construction specifications. Survey control points are often placed along the sides of the test fill and consist of pins set back from both sides of the edge of the test fill at approximately 6-m (20-ft) intervals. Markings are placed on the outside edges of the geosynthetics in the test fill so the relative movement between the geosynthetics can be monitored. Control points are typically surveyed immediately after construction and every 5 days thereafter for the life of the test fill. After completion of the test fill, a 6-m by 6-m (20-ft by 20-ft) section should be carefully dismantled to inspect for damage to the geosynthetics.

(b) Work plan. The Contractor should be required to submit a detailed work plan describing all aspects of the proposed test fill section construction and monitoring. This plan should include scale drawings, survey procedures, test procedures, and equipment to be used. The Contractor should also submit a post construction report which includes as-built drawings, test results, survey data, and conclusions. The Contractor should be required to videotape construction and dismantling of the test fill.

d. Borrow areas.

(1) General. Borrow site investigations may be performed during either the predesign or design phase. The investigations should determine if adequate borrow material is available for the various layers of the cover. It is important to ensure that an excess of each borrow type is available in case some of the material at the borrow site later proves to be unacceptable or investigations indicate the landfill cover is larger than anticipated. The availability of both on-site and off-site borrow should be evaluated. On-site borrow will normally result in substantial cost savings over off-site materials. Off-site materials must be purchased by the Contractor and hauled to the project. This stresses access roads and may be a concern to the public due to increased traffic volume. If on-site borrow is available, investigations are required to define the nature and extent of the borrow source. A borrow area grading plan is sometimes required in the plans along with profiles showing excavation limits and subsurface features. Haul roads from the borrow source to the landfill location must also be assessed. On-site borrow areas can be used for wetland mitigation. Regulatory issues concerning the National Environmental Policy Act (NEPA) and the Clean Water Act need to be addressed when evaluating the use of borrow areas for wetland mitigation. Borrow sources are required for topsoil, select fill, random fill, clay, and granular materials. Granular materials are required for drainage layers, gas collection layers, and road surfacing. Larger diameter materials may also be required for ditch linings, gabion structures, and stilling basins.

(2) Design criteria. Potential borrow sites should be characterized by determining material types and their extent, natural water content, and depth to ground water. In addition, soil samples should be collected from all materials that will be used in construction. These samples will be used to determine specific geotechnical engineering properties of the soils. The type of sample and amount of material required is dependent on the type of tests that will be performed. Samples should also be taken from each borrow site to verify that the soils are not contaminated. The chemical testing required is site specific and a chemist should be involved in determining the chemical testing requirements. Testing requirements are typically based on 40 CFR 261, Subpart C, Characteristics of Hazardous Waste. Typical geotechnical tests performed on borrow soils are discussed in paragraph B-2.

e. Ground water monitoring.

(1) General. Closure requirements mandate that the upper aquifer beneath the landfill be monitored to determine if the landfill is causing degradation of ground water quality. Ground water monitoring wells are placed both up and down gradient from the landfill and are sometimes located within the landfill footprint. Prior to construction of the cover, all existing monitoring wells should be evaluated to determine their usefulness for long term monitoring. If any monitoring wells are located within the limits of construction, it will be necessary to protect, raise, or relocate the wells. If wells are to be abandoned, well abandonment procedures promulgated by the state or other government agencies should be described in the specifications.

(2) Design criteria. The requirements for monitoring ground water at solid waste management units such as hazardous waste landfills are described in 40 CFR 264 Subpart F - Releases from Solid Waste Management Units. Ground water monitoring well design criteria are described in EM 1110-1-4000. Guide specification CEGS-02671 should be used in contract documents to specify construction requirements for monitoring wells. Other documents which may be useful in designing a ground water monitoring program include the following:

- EPA 530/R-93/001, RCRA Ground-Water Monitoring: Technical Enforcement Guidance Document.

- EPA 600/4-89/034, Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells.

- ASTM D 5092-90, Recommended Practice for Design and Installation of Ground-Water Monitoring Wells in Aquifers.

- ASTM D 5299-92, Guide for the Decommissioning of Ground Water Wells, Vadose Zone Monitoring Devices, Boreholes and Other Devices for Environmental Activities.

f. Cover grading requirements. Development of the grading plans for the various layers is an iterative process. Grading plans are normally developed for the random fill, clay barrier, and top soil layers. The grading plans should be well defined by horizontal and vertical control such that the cover grades can be easily staked in the field. The final slopes must reflect minimum grade requirements after settlement and must accommodate both internal and surface drainage requirements. The final slopes must also reflect stability considerations. In general, minimum slopes after settlement should be greater than 3 percent to maintain surface drainage and maximum slopes should not exceed 1V:3H due to cover stability considerations and to assure safe operation of maintenance equipment. The grading plan should also identify features such as perimeter ditches, drainage terraces, and drop structures. To ensure that the various layers meet the design grades, each layer must be surveyed after construction.

g. Cover penetrations.

(1) General. Penetrations through the landfill cover are required for gas vents, monitoring wells, and other purposes. However, the number of penetrations should be minimized. Geomembranes should be attached to the penetrating object in a way that ensures a water tight seal but still allows for movement due to settlement or horizontal displacement.

(2) Design criteria. Pipe penetrations extending through clay, geomembrane, and GCL layers should be constructed as shown in EPA/600/R-93/182. Most geomembrane manufacturers, fabricators, or installers have their own typical penetration details. Therefore, in many cases, it is only necessary to show locations of the penetrations on the drawings and note that penetration details must be in accordance with approved geomembrane manufacturer, fabricator, or installer details. GCL penetration details should be as recommended by the GCL manufacturer. As a minimum, pipe penetrations should incorporate a collar of GCL wrapped around the pipe and securely fastened. Dry bentonite should be placed around the penetration for additional protection. Dry bentonite should also be placed around penetrations through compacted clay liners.
Pipes that penetrate deeply into the waste material are likely to settle at a different rate and to a smaller magnitude than the adjoining landfill cover. The differential settlement between the well and the cover system creates stress concentrations at the boot connection which can tear the geomembrane away from the pipe. Slip couplings are typically used in this situation to allow differential movement while maintaining a water tight seal.

h. HELP model description and application.

(1) General. The HELP model is a computer program which is utilized to evaluate the overall performance of a cover system and its individual components. HELP models the hydrologic processes occurring in a landfill system including surface runoff, infiltration, evapotranspiration, soil moisture storage, lateral drainage, and leachate production. The HELP model is used to estimate landfill cover effectiveness, drainage layer flow, head build-up in select fill, and leachate collection system flow. It can also be used to perform comparative analyses for drainage layers (geonet versus granular material) and low permeability layers (clay, GCLs, and geomembranes).

The HELP model requires three general types of input data: climatological, geometric, and material characteristics. The model has climatological data stored for numerous locations throughout the United States. The climatological data used in the model should be proximate to the site location. The geometric parameters are derived from design considerations and the layout of the site. The required geometric input data includes the number of cover system components, layer thickness, layer type, drainage layer slope and maximum length, and the landfill area. Material parameters are required as input into the HELP model for each layer of the cover system, the waste, and the foundation material. The required material input data includes initial water content, porosity, field capacity, wilting point, and hydraulic conductivity.

(2) Design criteria. The version of the HELP model currently being used is Version 3. EPA/600/R-94/168a and b provide guidance on the use of the HELP model.

i. *Leachate control*. Leachate seeps exiting from the landfill surface need to be identified and located during predesign activities. A leachate collection blanket consisting of either granular fill or a geonet coupled with a conveyance pipe and outlet are sometimes required to control these seeps. Uncontrolled leachate seeps can cause a build up of hydrostatic pressure behind the low-permeability layer resulting in decreased stability of the cover system. After the leachate is collected, it must be stored and ultimately treated, either on- or off-site.

j. *Cover surface runoff and erosion control requirements*.

(1) General. Erosion of the final cover is controlled by vegetation, drainage terraces, and armored drop structures. The surface runoff system must be capable of conveying runoff down the side slopes without creating erosion rills and gullies. The erosion control features should be designed so that long term maintenance is minimized. Diversion structures may also be needed to prevent water from running onto the landfill cover and causing erosion. After drainage is directed off of the cover, perimeter drainage features such as ditches, gabions, or storm sewers are required to carry the water away from the toe of the landfill.

(2) Design criteria.

(a) Terraces. Steep landfill side slopes are likely to cause erosion unless controls are included in the design. Terraces are used to reduce erosion, reduce sediment content in runoff water, and conduct surface runoff to a stable outlet or drop structure. Terraces are normally trapezoidal in shape and have a minimum depth of 300-600 mm (1-2 ft). Terraces should have enough capacity to control the design runoff event which is typically the result of a 25- to 100-year rainfall frequency. States often dictate the runoff event used for design. Flow velocity is dependent upon channel slope, friction, discharge depth, and flow quantity. The flow velocity must be analyzed for all terraces, ditches, and drop structures to ensure erosion will not occur. If grass lined channels are not adequate, riprap, grout bags, erosion control mats, or gabions can be used to armor the side slopes and bottoms of terraces. The length of drainage terraces is controlled by flow capacity and non-erosive velocity requirements. Drainage terraces can also function as both an anchor for geosynthetics and a buttress for cover soils to improve cover stability.

(b) Drop structures. Terraces normally discharge into collection ditches or drop structures that descend down the steep slopes of a cover. Depending on the slope, a drop structure may be constructed of either grass, erosion control mats, riprap, or gabions. As with the terraces, the drop structures are usually trapezoidal in shape and must be hydraulically sized. A stilling basin at the toe of the cover is sometimes required to dissipate flow velocities prior to discharging the water off-site.

(c) Perimeter drainage control. Surface runoff from the cover should be controlled to prevent adverse impacts to adjoining properties and receiving waterways. Surface runoff should be controlled by collecting the water in lined or unlined perimeter channels or storm sewers.

(d) Off-site discharge control. If a final cover functions as designed, there should be an increase in both the total volume and the peak discharge of surface runoff leaving the site. The impact to the receiving stream of increased runoff volumes should be a design consideration. In addition, the potential downstream impacts of increased sedimentation both during construction and during normal project operations should be assessed. Off-site discharge can be regulated with detention ponds which provide water storage and trap sediments. In some cases, natural drainage away from the site does not exist; therefore, it may be necessary to design runoff storage, pumping, and discharge equipment. State and local regulations must be assessed when discharge patterns are changed. National Pollution Discharge Elimination System (NPDES) requirements for storm water discharges must also be assessed. Detention pond outlet works typically have a drop inlet riser pipe leading to a conduit that runs under the ponds embankment. Perforations placed in the riser pipe allow water to be discharged at a predetermined rate. A small gate is sometimes included in the design of the outlet structure. This provides a means of containing contaminated runoff during regrading and construction.

(e) Temporary erosion control measures. Vegetative cover, drainage terraces, drop structures, perimeter ditches, and detention ponds are used as permanent runoff and erosion control measures. During construction, refuse and soil will be exposed to the elements. Temporary erosion control measures such as straw, hay bales, erosion control fabric, mats, and silt fences are required to prevent erosion during construction. Requirements for erosion control should be specified in the contract documents.

(f) Floodplain considerations. Construction of the cover near a waterway may require placement of material within a floodplain. This may increase river stages and could result in greater flood damage to surrounding properties. Consequently, it may be necessary to design diversion channels, levees, or provide other flood protection measures to minimize impacts to surrounding properties. Erosion control materials may also need to be placed on the side slopes of the landfill.

(g) Hydrologic models. Discharge frequency relationships for landfills are based on a rainfall-runoff analysis using models such as the Corps of Engineers HEC-1 Flood Hydrograph Model. For purposes of modelling, the landfill should be divided into subcatchments and distinct drainage channels. The Kinematic Wave Method can be used to calculate rainfall runoff transformation. The landfill cap is often considered to be virtually impervious. Channel routing can be accomplished using the Muskingum-Cunge Method. Precipitation data should be obtained from the National Weather Service (NWS) Technical Paper No. 40 entitled “Rainfall Frequency Atlas of the United States” and NWS Technical Memorandum HYDRO-35, “Five to 60 Minute Precipitation Frequency for the Eastern and Central U.S.” Storage and outflow from detention ponds can be determined by calculating inflows and routing these flows through the pond according to the modified Puls method. This method uses a storage volume versus elevation relationship and an outflow capacity versus elevation relationship.

k. *Universal soil loss equation*.

(1) General. The Soil Conservation Service developed the Universal Soil Loss Equation for use in determining terrace requirements for crop land on slopes. The equation has also been used for landfills to determine the maximum vertical spacing between terraces and to estimate sediment transport into detention ponds.

(2) Design criteria. The terraces should be spaced such that soil erosion is no greater than 0.45 kg/m^2 (2 tons per acre) per year. Some states have developed their own criteria for terrace sizes and spacing. The book entitled *Erosion and Sediment Handbook* (Goldman et al. 1986) provides guidance in the use of the Universal Soil Loss Equation.

B-5. Civil Design

There are many other features that must be addressed during design which are integral components of a landfill cover construction project. These features are discussed in the following paragraphs.

a. *Site access routes*.

(1) General. Both public and private access routes to the site need to be investigated to ensure they can handle the construction traffic. The Contractor should be required to maintain any access routes including post-construction rehabilitation, if necessary. Aggregate surfaced roads may need to be built to allow access of construction vehicles or for operation and maintenance of the landfill.

(2) Design criteria. Aggregate surfaced roads should be designed in accordance with TM 5-822-12. Several guide specifications are available for the construction of roadways.

b. *Utility considerations*. The contract documents should identify existing utilities, relocation requirements, and service requirements for construction trailers, landfill gas collection systems, etc.

c. *Staging areas and phasing requirements*. The contract documents should identify acceptable locations for support facilities, storage areas, and parking. Construction phasing requirements should also be identified in the contract documents to prevent the uncontrolled migration of contaminants, surface runoff, and dust.

d. *Decontamination facility*.

(1) General. The Contractor must decontaminate all vehicles and equipment which enter the exclusion zone or contamination reduction zone. The contract documents should address the requirements for a decontamination facility and for the treatment and disposal of rinsate water. The final disposition of the decontamination facility should also be addressed. The Contractor should be required to submit a plan as part of the Site Health and Safety Plan which describes vehicle, equipment, and personnel decontamination procedures.

(2) Design criteria. The decontamination facility typically consists of 150-300 mm (6-12 in.) of granular material underlain by a protective geotextile and a geomembrane 1.0 mm (40 mils) in thickness. More elaborate designs may be used if the decontamination facility will be operated for a significant period of time. To minimize the volume of decontamination water, a temporary cover should be used to shed rainfall when the facility is not in use. Rinsate water is collected by gravity into a polyethylene or precast concrete storage tank which is typically about 3 cu m (100 cu ft) in volume. Treatment and disposal of the rinsate water and sediments should be in accordance with all state and federal regulations. Federal disposal regulations are described in 40 CFR Parts 260-268. Rinsate water is typically disposed of after on-site treatment or is transported to an off-site treatment facility. Sediments collected by the decontamination facility are often placed beneath the landfill cover. If the decontamination water and sediments are defined as hazardous wastes and are to be taken off-site, the Contractor must manifest the materials in accordance with 49 CFR Parts 100-180 and 40 CFR Part 263. The materials must be transported by a certified hazardous waste hauler and the Treatment, Storage, and Disposal Facility (TSDF) must have the appropriate EPA and state permits. The Contractor should submit the names of all haulers and TSDF facilities proposed for use. Chemical test results, manifests, Land Disposal Restriction (LDR) notification forms, and certifications of final treatment/disposal should also be submitted. See EP 200-1-2 for more detailed information on this subject.

e. *Security fencing*.

(1) General. Chainlink security fencing is often used at the landfill boundary. The fence normally has a standard single outrigger with three strands of barbed-wire on the outrigger. The fence fabric should be a minimum of 1.8 m (6 ft) in height.

(2) Design criteria. Guide specification CEGS-02831 should be used in the contract documents to specify fencing requirements.

f. *Demolition*.

(1) General. Structures that will be demolished and debris that will be removed should be identified on the contract documents. Special circumstances, such as asbestos containing debris, should be considered during design.

(2) Design criteria. When demolition is required, guide specification CEGS-02050 should be edited and included in the contract documents. Transportation and disposal regulations must be considered if demolition materials or debris contain hazardous waste.

g. *Clearing and grubbing*.

(1) General. Clearing and grubbing is performed prior to placement of the random fill layer. Grubbing on hazardous waste landfills is often not performed or is minimized due to the added costs for disposal of hazardous materials and health and safety concerns.

(2) Design criteria. The limits of clearing and grubbing should be identified on the drawings. Guide specification CEGS-02110 should be edited and included in the contract documents. The method of disposal for cleared and grubbed materials should be clearly stated in the specification. Cleared and grubbed material is often placed beneath the landfill cover in the lower regions of the random fill layer.

B-6. Health and Safety

a. *General*. An industrial hygienist is responsible for the health and safety issues of a final cover design. Elements to be addressed include the following: site description and contamination characterization; hazard/risk analysis; staff organization, qualifications, and responsibilities; training; personal protective equipment; medical surveillance; radiation dosimetry; exposure monitoring/air sampling; heat/cold stress monitoring; standard operating safety procedures, engineering controls and work practices; site control measures; personal hygiene and decontamination; equipment decontamination; emergency equipment and first aid requirements; emergency response and contingency procedures; accident prevention; and logs, reports, and record keeping. If predesign investigations are conducted, a Site Safety and Health Plan (SSHP) is required.

b. *Design criteria*. Detailed safety and health requirements are described in ER 385-1-92. A Health and Safety Design Analysis should be included as a chapter of the project design analysis to describe the decision logic for safety and health requirements which will be specified. Guide specification CEGS-01110 should be edited based on the design analysis and included in the contract documents.

B-7. Chemistry

a. *General*. A chemist should be responsible for the chemistry aspects of a final cover design. This includes identification of requirements for chemical sampling and analysis conducted during the construction or maintenance phase of the project such as general air quality, off-gas testing, leachate, borrow soil, ground water, and miscellaneous testing for potential hazardous waste.

b. *Design criteria*. Detailed requirements for chemical analyses are described in ER 1110-1-263. The requirements of ER 1110-1-263 should be followed for any predesign chemistry testing also. Guide specification CEGS-01450 should be edited and included in the contract documents.

B-8. Operation and Maintenance Requirements

The Construction Contractor is normally required to perform site operation and maintenance on the project for a period of one year after completion. Parameters such as ground water, leachate generation, air quality, underground gas migration, and cover effectiveness should also be monitored by the Contractor. Baseline conditions must be measured either prior to or immediately after construction depending upon the parameter. Consistent and accurate record keeping during the post closure period is essential.

a. *Ground water*. Up and down gradient monitoring wells must be sampled after closure. The frequency of monitoring and contaminants tested for will be specified by the EPA Regional Administrator or state regulatory authorities. Samples are typically collected from ground water monitoring wells at a frequency of once every one to three months during the first year after construction; however, this frequency should be a function of the database available for the site. During each round of sampling, the ground water elevation should also be determined and changes in ground water flow conditions evaluated. Periodic maintenance of the monitoring wells may be necessary to assure proper operation.

b. *Leachate*. Leachate should be monitored at discharge outlets for flow rate as well as chemical composition. Leachate discharge should decrease with time once the cover is constructed.

c. *Landfill gas*. The Contractor should operate and maintain the landfill gas extraction system during the one year post closure period. Landfill gas concentrations should be monitored at compliance points as determined by the EPA Regional Administrator or state regulatory authorities. Compliance points may include gas monitoring probes, boundary monitoring stations, well heads for passive systems, or flares for active systems. Monitoring at the compliance points is typically performed once every two to four weeks for the first year after construction.

d. *Settlement*. When settlement is anticipated to be a problem, settlement markers should be installed on the final cover above the geomembrane. The Contractor should place additional select fill and top soil in areas where settlement has occurred. These areas should then be reseeded.

e. *Slope stability*. Slope stability is monitored by visual inspection. Movement markers can also be placed on the steepest slopes of the cover and surveyed annually or more often if required.

f. *Landfill cover*. The Contractor will be required to maintain the effectiveness of the final cover including maintaining the cap subdrainage system, establishing the vegetative cover, and repairing erosion damage. Reseeding should be performed in areas that have poor vegetative cover. The landfill cover should be mowed once or twice per month from May through October once the vegetative cover has been established. The cover surface should also be inspected for rodent holes. Irrigation requirements must be identified for covers located in arid climates.

g. *Runoff controls*. Drainage terraces, ditches, and drop structures should be inspected to assure that erosion is not occurring and the erosion control features are performing as designed. The detention pond should be inspected to assure there is sufficient storage available for sediment. Periodic dredging of sediment may be required.

h. *Other features*. Other features such as fences and perimeter access roads should also be maintained by the Contractor during the one year maintenance period.

i. *Inspections*. The Contractor is typically required to perform an inspection of the site one to two times per month. The inspection should monitor the following items: condition of the cover, outlets to the cover subdrainage system, settlement, slope stability, runoff control structures, monitoring wells, gas extraction system, fences, and access roads. The Contractor should furnish an inspection report within 7 days of the completion of each inspection. Inspection reports should include a written summary of deficiencies noted, repairs performed, and other significant operational events. The report should also include instrumentation readings taken.

j. *Maintenance*. The Contractor should notify the contracting officer in writing at least 5 working days in advance of conducting any major maintenance activities. A representative of the contracting office should be present during all major maintenance activities. The Contractor should prepare a maintenance completion report after any major maintenance has been performed.

B-9. Environmental and Regulatory Compliance

Table B-2 provides a list of potentially applicable or relevant and appropriate federal standards, requirements, and criteria. The purpose of this table is to provide a brief description of the federal regulations which may be applicable to a hazardous waste site where a landfill cover is being considered.

B-10. Potential List of Drawings

Provided below is a list of potential drawings that should be included in the contract documents. Not all drawings will be applicable to every project.

Cover Sheet
Index of Drawings
Abbreviations
Legend
Vicinity Map
Location Map
Existing Site Conditions (including utilities)
Test Pit and Boring Location Plan
Contractor Access Plan
General Plan
Horizontal and Vertical Control
Removal Plan
Demolition-Photo Location Plan
Demolition Photos
Electrical Distribution Plan
Site Control Plan
Initial Grading Plan
Random Fill Grading Plan
Low Permeability Clay Layer Grading Plan
Final Grading Plan
Erosion Control Plan (Temporary)
Cap Cross Sections
Cap Detail Drawings; Anchor Trench, Collection Pipes and Toe Drains
Gabion and Riprap lined Channel Cross-Sections and Details
Detention Pond Excavation, Embankment and Outlet Works
Storm Drain Plans, Profiles and Details
Area Inlet Details, Manhole Details
Cover Drainage Layer Collection System Plan
Gas Extraction Well Details
Gas Monitoring Probe Details
Gas Collection Header Pipe Details
Gas Blower Flare and Piping Details
Wash-down Area Cross-Sections and Details (Decon Pad)
Settlement Monument, Benchmark and Penetration details
Monitoring Well Details
Piezometer Details
Chain Link Fence Details
Chain Link Gate Details
Project Right-of-Way Map
Record of Borings (Geological Profile Sheets)
Borrow Area Grading Plan, Sections, and Soil Test Data
New Utility Drawings
New Access Road Profiles and Sections
Structural Drawings
Dewatering Plan
Mechanical Drawings
Electrical Drawings

Table B-2
Potentially Applicable or Relevant and Appropriate Federal Standards, Requirements and Criteria

Standard Requirement, Criteria, or Limitation	Citation	Description
Safe Drinking Water Act	42 USC 300g	
National Primary Drinking Water Standards	40 CFR Part 141	Establishes health based standards for public water systems (maximum containment levels).
National Secondary Drinking Water Standards	40 CFR Part 143	Establishes welfare based standards for the public water systems (secondary maximum containment levels).
Maximum Contaminant Level Goals	PL 99-300, 100 Stat. 642 (1986)	Establishes drinking water quality goals set at levels of unknown or anticipated adverse health effects, with an adequate margin of safety.
Clean Water Act	33 USC 1251-1376	
Water Quality Criteria	40 CFR Part 131	Sets criteria for water quality based on toxicity to aquatic organisms and human health.
National Pollution Discharge Elimination System (NPDES)	40 CFR 122 &124	Establishes permit requirements for discharge of pollutants into the nation's waters.
Clean Air Act	42 USC 7401-7642	Establishes a regulatory system for air pollution from stationary and mobile sources.
Solid Waste Disposal Act (SWDA)	42 USC 6901-6987	
Resource Conservation and Recovery Act (RCRA)	PL 94-580 90 Stat. 2795	Enacted as an amendment to the Solid Waste Disposal Act.
Guidelines for the Land Disposal of Solid Wastes	40 CFR 241	Establishes requirements and procedures for land disposal of solid wastes.
Criteria for Classification of Solid Waste Disposal Facilities	40 CFR Part 257	Establishes criteria for use in determining which solid waste disposal facilities and practices pose a reasonable probability of adverse effects on health or the environment.
Hazardous Waste Management System: General	40 CFR Part 260	Establishes definitions as well as procedures and criteria for modification or revocation of any provision in 40 CFR Parts 260-265.
Identification and Listing of Hazardous Waste	40 CFR Part 261	Defines those solid wastes which are subject to regulations as hazardous wastes under 40 CFR Parts 262-265.

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**Table B-2
(Continued)**

Standard Requirement, Criteria, or Limitation	Citation	Description
Standards Applicable to Generators of Hazardous Wastes	40 CFR Part 262	Establishes standard for generators of hazardous waste.
Standards Applicable to Transporters of Hazardous Wastes	40 CFR Part 263	Establishes standards which apply to persons transporting hazardous waste within the U.S. if the transportation requires a manifest under 40 CFR
	Part 262.	
EPA Toxic Pollutant Standards	40 CFR 129	Establishes effluent standards or prohibitions for toxic pollutants.
Solid Waste Disposal Facilities Criteria	40 CFR 258	Establishes minimum criteria for municipal solid waste landfills.
Standards for Owners and Operators of Hazardous Waste Treatment, Storage and Disposal Facilities (TSD)	40 CFR Part 264	Establishes national standards which define the acceptable management of hazardous waste for owners and operators of facilities which treat, store, or dispose of hazardous waste.
General Facility Standards	Subpart B	Establishes requirements for facility ID numbers, waste analysis inspections, and training.
Preparedness and Prevention	Subpart C	Facilities must be designed, constructed, maintained, and operated to minimize possibility of fire, explosion, or unplanned release of hazardous waste.
Contingency Plan and Emergency Procedures	Subpart D	Establishes requirements for TSD facilities to develop a contingency plan and design to minimize hazard to human health or the environment.
Manifest System Record Keeping and Reporting	Subpart E	Establishes requirements for manifest systems, signatory responsibilities, and reporting schedules.
Releases From Solid Waste Management Units	Subpart F	Establishes requirements for operation and maintenance of leak detection system; sets corrective action criteria.
Closure and Post Closure	Subpart G	Establishes criteria for closure performance standards; must control, minimize or eliminate escape of hazardous waste to the extent necessary to protect human health and the environment.

(Sheet 2 of 5)

**Table B-2
(Continued)**

Standard Requirement, Criteria, or Limitation	Citation	Description
Financial Requirements	Subpart H	Owner or operator of a TSD facility must establish financial assurance for closure of the facility.
Use and Management of Containers	Subpart I	Establishes standards for containers holding hazardous waste, containment areas.
Tanks	Subpart J	Establish standards for tanks, tank integrity testing, testing, design and installation standards, and leaks containment.
Surface Impoundment	Subpart K	Establishes liner standards, monitoring and inspection requirements.
Waste Piles	Subpart L	Establishes standards for precipitation runoff or leachate prevention, design and operation criteria, and monitoring and inspection.
Land Treatment	Subpart M	Establishes criteria for TSD to ensure that hazardous waste placed in treatment zones are degraded, transformed, or immobilized within the treatment zone.
Landfills	Subpart N	Establishes requirements for design, operation, monitoring, closure and post closure care.
Interim Status Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities	40 CFR Part 265	Establishes minimum standards for management of hazardous waste during the period of interim status and final closure or until post-closure responsibilities are fulfilled.
Standards for Management of Specific Hazardous Waste & Specific Types of Hazardous Waste Management Facilities	40 CFR Part 266	Establishes requirements which apply to recyclable materials that are reclaimed to recover economically significant amounts of gold and silver.
Interim Standards for Owners and Operators of New Hazardous Waste Land Disposal	40 CFR Part 267	Establishes minimum standards that define the acceptable management of hazardous Facilities waste for new land disposal facilities.

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Table B-2
(Continued)

Standard Requirement, Criteria, or Limitation	Citation	Description
Land Disposal Restrictions	40 CFR 268	Identifies hazardous wastes that are restricted from land disposal and defines those limited circumstances under which a prohibited waste may continue to be land disposed.
Underground Storage Tanks	40 CFR Part 280	Establishes regulations related to underground storage tanks.
Toxic Substance Control Act	15 USC 2601-2629 40 CFR Part 700	Establishes requirements for testing of new chemicals prior to distri bution, reporting of chemicals that present a substantial risk to human health and the environment, sets stan dards for records keeping and radon investigation.
Occupational Safety and Health Act	29 USC 651-678	Regulates worker health and safety.
DOT Hazardous Material Transportation Regulation	49 CFR Parts 107, 171-177	Regulates transportation of hazardous materials.
Asbestos Abatement Projects	40 CFR Part 763 Subpart G	Establishes requirements which must be followed during asbestos abatement projects.
Hazardous Chemical Reporting Community Right-to-Know	40 CFR 370	Establishes reporting requirements which provide the public with important information on the hazardous chemicals in their communities.
Polychlorinated Biphenyls Manufacturing, Processing, Distribution in Commerce, and Use Prohibitions	40 CFR Part 761	Establishes prohibitions of, and require ments for the manufacture, processing, distribution in commerce, use, disposal, storage, and marking of PCBs and PCB items.
Archaeological and Historic Preservation Act	16 USC 469 40 CFR 6.301(c)	Establishes procedures to provide for preservation of historical and archaeological data which might be destroyed through alteration of terrain as a result of a federal construction project or a federally licensed activity or program.
Archaeological Resources Protection Act (1979)	93 Stat. 721 16 USC 470	This act requires a permit for any exca-vation or removal of archaeological resources from public or Indian land.

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**Table B-2
(Concluded)**

Standard Requirement, Criteria, or Limitation	Citation	Description
National Historic Preservation Act	16 USC 470 40 CFR 6.301(b) 36 CFR Part 800	Requires federal agencies to take into account the affect of any federally assisted undertaking or licensing on any district, site, building, structure, or object that is included in or eligible for the Register of Historic Places.
Historic Sites, Buildings, and Antiquities Act	16 USC 461-467 40 CFR 6.301(a)	Requires federal agencies to consider the existence and location of landmarks on the National Registry of Natural Landmarks to avoid undesirable impacts on such landmarks.
Fish and Wildlife Coordination Act	16 USC 1531-666 40 CFR 6.302(g)	Requires consultation when a federal department or agency proposes or authorizes any modification of a stream or other water body and adequate provision for protection of fish and wildlife resources.
Endangered Species Act	16 USC 1531-1543 50 CFR Parts 17, 402 40 CFR 6.302(g)	Requires that federal agencies ensure that any action authorized, funded, or carried out by the agency is not likely to jeopardize the continued existence of any threatened or endangered species or destroy or adversely modify critical habitat.
Executive Order on Floodplains Management	EO No. 11,988 40 CFR 6.302(b) & Appendix A	Requires federal agencies to evaluate the potential effects of actions they may take in a floodplain to avoid, to the extent possible, the adverse impacts associated with direct and indirect development of the floodplain.
Executive Order on Protection of Wetlands	EO No. 11,990 40 CFR 6.302(a) & Appendix A	Requires federal agencies to avoid, to the extent possible, the adverse impacts associated with the destruction or loss of wetlands and to avoid support of new construction in wetlands if a practicable alternative exists.
Wild and Scenic Rivers Act	16 USC 1271-1287 40 CFR 6.302(e)	Establishes requirements applicable to water resources projects affecting wild, scenic, or recreational rivers within or involved in studies for inclusion in the National Wild and Scenic Rivers System.
National Environmental Policy Act (NEPA)	PL 91-190 42 USC 4321 et. seq. 33 CFR 230 and 325 40 CFR 1500-1508	For every project that may affect the environment and hence needs a federal permit for operation, NEPA requires an Environmental Impact Statement (EIS). The EIS quantifies environmental impacts and benefits, and describes and compares alternatives.

(Sheet 5 of 5)

Leachate Collection System Plan, Profile, Section and Details
Wetlands Mitigation Area Plan, Section and Details

B-11. Potential List of Specification Sections

Provided below is a list of potential specifications that should be included in the contract documents. Not all specifications will be applicable to every project. Corps of Engineers Guide Specifications for Military Construction are shown when available. If no guide specification exists, experience from previous sites or manufacturer specifications should be modified by the design engineer to create a construction specification.

DIVISION 1 - GENERAL REQUIREMENTS

01110	Safety, Health, and Emergency Response
01300	Submittals Descriptions
01305	Submittal Procedures
01440	Contractor Quality Control
01450	Contractors Chemical Quality Control
01XXX	Summary of Work
01XXX	Order of Work
01XXX	Contractors Use of Site
01XXX	Pre Construction and Pre Work Conference
01XXX	Progress Meetings
01XXX	Special Clauses
01XXX	Measurement and Payment
01XXX	Special Project Features
01XXX	Warranty of Construction
01XXX	Construction General
01XXX	On-Site Camera
01XXX	Dust Control
01XXX	Spill and Discharge Control Plan
01XXX	Vent Gas and Off-Site Air Monitoring
01XXX	Vehicle and Bulky Debris Removal
01XXX	Environmental Protection
01XXX	Security
01XXX	Regulatory Requirements
01XXX	Decontamination and Disposal
01XXX	Surveys for Record Drawings
01XXX	Photographic Documentation
01XXX	As-Built Drawings
01XXX	Project Record Documents
01XXX	Temporary Utilities and Controls
01XXX	Support Facilities
01XXX	Demobilization and Project Close Out
01XXX	Operation and Maintenance

DIVISION 2 - SITE WORK

02050	Demolition
02080	Asbestos Abatement
02110	Clearing and Grubbing
02210	Grading
02222	Excavation, Trenching, and Backfilling for Utilities Systems
02233	Graded-Crushed-Aggregate Base Course
02234	Subbase Course
02271	Geomembrane Barrier for Landfill Cover
02272	Separation/Filtration Geotextile
02273	Geonet
02442	Geosynthetic Clay Liner
02443	Low Permeability Clay Layer
02546	Aggregate Surface Course
02671	Ground Water Monitoring Wells
02720	Storm Drainage System
02730	Sanitary Sewers
02831	Chain-Link Fence
02935	Turf
02950	Trees, Shrubs, Ground Covers, and Vines
02XXX	Well Abandonment
02XXX	Hazardous Material Excavation and Handling
02XXX	Excavation and Random Fill for Landfill Cover Systems
02XXX	Select Fill and Topsoil for Landfill Cover Systems
02XXX	Test Fill Sections
02XXX	Stone Protection
02XXX	Wire Mesh Gabions
02XXX	Leachate Collection System
02XXX	Sand/Gravel Drainage Layer
02XXX	Geogrid Reinforcement Material
02XXX	Gas Venting System
02XXX	Gas Monitoring Probes
02XXX	Drainage Structure
02XXX	Temporary Erosion and Sediment Controls
02XXX	Permanent Surface Water Controls
02XXX	Decontamination Facility
02XXX	Roadways and Parking Areas
02XXX	Water Lines
02XXX	Contaminated Liquids Removal
02XXX	Subdrainage System for Landfill Cover Systems

02XXX	Site Maintenance
02XXX	Demobilization and Project Close Out
02XXX	Post-Construction Maintenance Activities

DIVISION 3 - CONCRETE

03100	Structural Concrete Formwork
03200	Concrete Reinforcement
03250	Expansion Joints, Contraction Joints, and Water Stops
03300	Concrete for Building Construction

DIVISION 5 - STEEL

05210	Steel Joists
05500	Miscellaneous Metal

DIVISION 11 - EQUIPMENT

11XXX	Centrifugal Blower
11XXX	Activated Carbon Adsorption System
11XXX	Off gas Treatment System

DIVISION 13 - SPECIAL CONSTRUCTION EQUIPMENT

13XXX	Landfill Gas Flare System

DIVISION 15 - MECHANICAL

15488	Gas Piping Systems
15XXX	Valves, Pipe Hangers, and Supports
15XXX	Thermal Insulation for Mechanical Systems
15XXX	Process Piping and Appurtenances

DIVISION 16 - ELECTRICAL

16XXX	Electrical Work

B-12. Quantity Tabulation Sheet for Cost Estimates

Provided below is a list of items that should be considered when developing a cost estimate for a landfill cover project. Not all items will be applicable to every project.

Description	Unit
All Other Items	Lump Sum
Site Preparation (Construction Trailers, Staging Areas, Parking Areas, etc.)	Lump Sum
Landfill Clearing	Hectares (Acres)
Site Clearing and Grubbing	Hectares (Acres)
Proof Rolling Landfill Surface	Hectares (Acres)
Decontamination Facility	Lump Sum
Chain Link Fence	Linear Meters (Linear Feet)
Access and Perimeter Roads and Ditches	Cubic Meters (Cubic Yards)
Access and Perimeter Road Surfacing	Kilograms (Tons)
Building Demolition and Debris Removal	Lump Sum
Asbestos Removal	Lump Sum
Utility Relocations and Extensions	Lump Sum
Monitoring Wells	Each or Linear Meters (Linear Feet)
Monitoring Well Abandonment	Each or Linear Meters (Linear Feet)
Detention Pond Excavation	Cubic Meters (Cubic Yards)
Detention Pond Outlet Works	Lump Sum
Detention Pond Embankment	Cubic Meters (Cubic Yards)
Riprap Lined Channels	Kilograms (Tons)
Gabion Structures	Kilograms (Tons)
Outfall Storm Sewer	Linear Meters (Linear Feet)
Piezometers	Each or Linear Meters (Linear Feet)
Leachate Collection System	Linear Meters (Linear Feet) or Lump Sum
Infiltration Conveyance and Discharge System	Linear Meters (Linear Feet)
Landfill Refuse Excavation	Cubic Meters (Cubic Yards)
Landfill Refuse Backfill	Cubic Meters (Cubic Yards)
Random Fill	Cubic Meters or Kilograms (Cubic Yards or Tons)
Gas Collection and Treatment System	Lump Sum
Gas Monitoring System-Probes	Each or Linear Meters (Linear Feet)
Gas Barrier System	Linear Meters or Kilograms (Linear Feet or Tons)
Impervious Clay Layer	Cubic Meters or Kilograms (Cubic Yards or Tons)
Geomembrane	Square Meters (Square Yards)
Sand/Gravel Drainage Layer	Kilograms (Tons)
Geonet	Square Meters (Square Yards)
Geotextile	Square Meters (Square Yards)
Select Fill	Cubic Meters (Cubic Yards)
Topsoil	Cubic Meters (Cubic Yards)
Turf	Hectares (Acres)
Temporary Erosion Control Features	Lump Sum
Gabion Structures on Landfill	Kilograms (Tons)
Settlement Monuments	Each

Operation and Maintenance	Lump Sum